Implementation of a normal incidence spectrometer on an electron beam ion trap

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Spectroscopic instrumentation is one of the keys to the exploration of high-temperature plasmas. The electron beam ion trap (EBIT) can serve as a tool for precise studies of highly charged ions in the laboratory and can help in setting spectroscopic standards for plasma studies. Recent efforts have focused on investigating the EUV, vacuum ultraviolet (VUV), and UV regimes. We present here the implementation of a 1 m normal incidence spectrometer for use on the Lawrence Livermore National Laboratory high-energy EBIT (Super-EBIT) for spectral analysis of line emission of highly charged ions. Using two different gratings, our study encompasses a wide range of wavelengths spanning the VUV through the visible. Examples of measurements of optical spectra from krypton and argon are given. © *1999 American Institute of Physics.* [S0034-6748(99)51901-1]

I. INTRODUCTION

Electron beam ion traps (EBITs) were developed as sources of trapped, highly charged ions for precision spectroscopic study. These unique instruments have proven to be able to provide excellent spectroscopic data of highly charged ions in the x-ray and visible regions of the electromagnetic spectrum, permitting a variety of measurements ranging from x-ray line diagnostics for fusion and astrophysical plasmas to studies of forbidden lines in the visible.[1–5] The spectroscopic instrumentation used so far has included solid state x-ray pulse height analysis systems, flat crystal, focusing crystal, as well as grating and prism spectrometers. Until now no spectroscopic studies have been reported that explore the entire ultraviolet region. We have used a normal incidence grating spectrometer which not only improves on the resolution of earlier measurements made in the visible using a prism spectrograph, but also permits studies in the ultraviolet (UV) and vacuum ultraviolet (VUV) down to wavelengths shorter than 1000 Å. The monochromator housing has been modified in order to mount a charge coupled device (CCD) detector, so that measurements over a range of wavelengths could be made in a single exposure. Such a sensitive multichannel detector accelerates the process of data taking and simplifies the data analysis compared to a conventional scanning monochromator.

II. EXPERIMENTAL ARRANGEMENT

The measurements described here were performed at the high-energy EBIT, dubbed Super-EBIT. At the core of EBIT is a tightly confined, monoenergetic electron beam which travels the length of the vacuum chamber. Ions or atoms are injected into EBIT using either a metal vapor vacuum arc (MeVVA) electrical discharge or by gas flowing through an injection port. These are sequentially ionized by the electron beam and trapped, radially by the space charge of the electron beam and axially by the potential well which is created by a set of three collinear drift tube electrodes. While trapped, the ions are collisionally stripped up to a range of charge states, the upper limit of which is determined by the ionization potential and by the energy of the electrons in the beam. Slots in the drift tubes provide optical and x-ray ports for observation of this trap region.[6,7] The beam diameter is typically about 70 μm[8] and thus can serve as an effective slit for high-resolution spectrometers.

A 1 m normal-incidence grating high-vacuum monochromator manufactured by Acton Research Corporation was used to observe VUV and visible spectral line radiation emitted from ions in Super-EBIT. A schematic of this arrangement is shown in Fig. 1. The spectrometer operates at a 15° deflection angle utilizing $f/10.4$ optics. The housing was

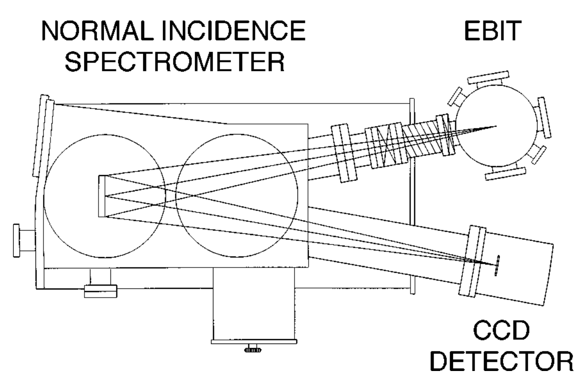

FIG. 1. Schematic of the normal-incidence grating spectrometer displaying its geometric relationship to EBIT and the detector. For measurements at wavelengths above the transmission cutoff of quartz, the bellows between the spectrometer and EBIT were replaced by quartz windows. Scanning over a range of wavelengths is achieved by rotating the grating.

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TABLE I. List of manufacturer's grating specifications for the two gratings used on EBIT. A more comprehensive list is available from Acton Research Corporation.

Grating (g/mm)	Blaze wavelength (Å)	Range (Å)	Resolution capability (Å)	Reciprocal linear dispersion (Å/mm)
300	7000	300–13000	0.56	33.3
600	3000	300–6500	0.28	16.6

modified (the entrance slit head removed) to mount the spectrometer to one of EBIT's optical ports, so that EBIT's electron beam could be placed at the normal entrance slit position of the spectrometer. A dual indexable grating mount allows the alternate use of two gratings without venting the spectrometer. We illustrate the use of this instrument with a 300 and 600 groove/mm grating. These gratings provided an overall wavelength coverage from around 1000 to over 8000 Å. The manufacturer's specifications for the gratings are listed in Table I. Instead of operating the instrument as a monochromator the exit slit was removed and replaced with a CCD detector so that a wavelength interval of 800 Å for the 300 groove/mm grating and of 400 Å for the 600 groove/mm grating was covered at any given spectrometer setting.

For measurements performed in the VUV (i.e., wavelengths below the transmission cutoff of quartz), no windows or optical filters of any kind could be used. This resulted in the housing of the spectrometer (at typically 8×10^{-8} Torr base pressure) being a gas load on the ultrahigh vacuum (UHV) of Super-EBIT, which typically runs at pressures of much less than 1×10^{-11} Torr. An increased pressure in the trapping region results in a higher collision frequency of the highly charged ions with residual gases, and thus in an increase of the probability of charge transfer reactions accompanied by a decrease of the attainable high charge states. For measurements above the cutoff of quartz, quartz windows were used to separate the EBIT vacuum from the spectrometer.

A further enhancement of the spectrometer performance was gained from the addition of internal light baffles. Light diffracted at angles other than those directly illuminating the detector, particularly direct, zero-order diffraction, was noticed to hit and reflect from the shiny walls (UHV-grade steel surface) of the spectrometer housing. For certain settings, this light could reach the photon detector and thus added to the scattered background signal. A series of black anodized aluminum foil baffles were placed around the wanted light path. Apparently not all of the reflections could be blocked yet, but a significant reduction in the stray light background was achieved.

The photon detector, a CCD camera from Photometrics, has a 25×25 mm^2, back-thinned, cryogenically cooled, CCD with nominal 25 μm pixel size. The scientific-grade CCD is sensitive from the x-ray range through the visible and beyond, and is operated *in vacuo*. The CCD is controlled by commercial software and the data stored as binary files. This software also allows the user to adjust the gain, the active region, and the pixel binning of the CCD. For much of the work here, a binning factor of 8 or 16 was used along the nondispersive direction, in order to increase the signal-to-noise ratio. No binning was used in the dispersive direction.

III. SPECTRAL MEASUREMENTS AND ANALYSIS

All spectral measurements were recorded as two-dimensional data arrays exhibiting not only the dispersion, but also—thanks to the rather stigmatic imaging conditions—some spatial information on the light distribution in the trap. This spatial information makes it easy in many cases to distinguish spectral lines that emanate from neutral atoms from those spectral lines that are emitted by trapped ions.[9] This is because gaseous elements are injected through a leak valve with an outlet nozzle close to the trap center. The ballistic trajectories of this neutral spray of atoms intersect the path of the electron beam in a region much shorter than the trap length. Excited states in these neutral atoms usually have short lifetimes and thus radiate close to where the ballistic atoms cross the beam path. After passing through the electron beam, those atoms that are not ionized either freeze out to the cryogenically cooled chamber surface or are pumped out of the vacuum vessel via several pumping pathways. Atoms that are ionized can become trapped; they can travel along the magnetic field until they are repelled by the electrostatic potential well walls. Hence they remain primarily within the confines of the 70 μm electron beam and travel back and forth along the 2 cm length of the trap. Therefore, in the two-dimensional spectra, transitions from ions appear as narrow, long lines, while transitions from neutral atoms appear much shorter in length.

For analysis the spectra were summed along the nondispersive direction of the CCD. This was done with a custom software program that also allows the user to filter spurious signals that are derived from either hard x rays or cosmic radiation events impinging onto the detector. These events are easily distinguished from the true signal since they produce hundreds of counts in a single pixel, whereas typical low-energy photons produce only a few counts. The filtered data are then stored as an ASCII file for off-line spectral analysis. However, the filtering algorithms are a field needing further improvement, as any automated judgement on event distributions in a two-dimensional (2D) array can be fallacious, and near coincidences of spurious and real events (as well as low-intensity data in the presence of CCD-related read-out noise) do happen.

A. Optical spectroscopy of krypton and argon

The wavelength region subtended by the detector is adjustable by rotation of the grating. Since EBIT is a very stable source, the full optical wavelength region can be stud-

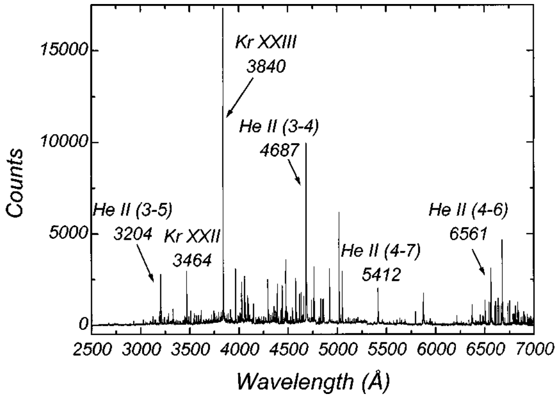

FIG. 2. Coalesced spectrum of krypton at an electron beam energy of 1.4 keV. The data were recorded using a 600 grooves/mm grating, combining 16 individual background-subtracted spectra, each integrated for 15 min. Several of the identified lines are marked including the strongest of the the $m \rightarrow 3$ and $m \rightarrow 4$ transitions of He II.

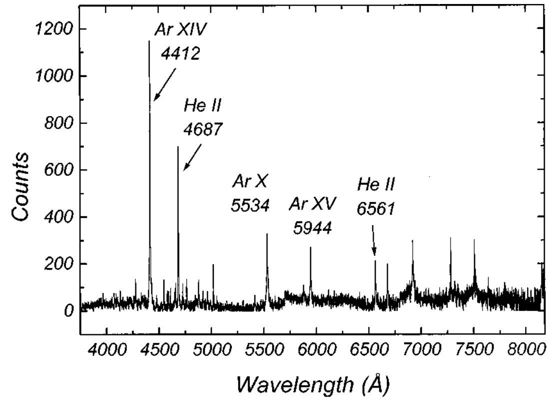

FIG. 3. Visible spectrum of argon at an electron beam energy of 10 keV. This spectrum was recorded using the 300 grooves/mm grating and combines seven background-subtracted sections. Each section was recorded in a 1 min exposure.

ied by sequentially recording adjoining wavelength regions. A spectrum of krypton measured with the 600 groove/mm grating is shown in Fig. 2. The spectrum covers the range of 2500–7000 Å and is a composite of 16 individual measurements. The operating parameters of EBIT were an electron beam energy of 1.4 keV and an electron beam current of 10 mA. We determined a resolving power of 1800 at 5000 Å with the linewidth remaining practically constant over the range of the spectrometer.

Each of the individual spectra making up the composite was integrated for 15 mins. Due to a high background in some of the spectra (resulting from internal reflections of light within the spectrometer) and the resulting need for background subtraction from each spectrum, the matching of adjacent components is not perfect. There also is the artificially introduced read-out noise and a certain read-out asymmetry from the fact that the exposure continues during the read-out. The 16 separate regions are still discernable, but this does not degrade the wavelength accuracy. As can be seen, many lines are present, particularly in the range 3500–5000 Å. Of particular note are two previously identified metastable Kr lines, 3464 Å Kr XXII[10] and 3840 Å Kr XXIII,[11] as well as He II lines at 3203 and 4685 Å, *M*-shell transitions, and 4542, 4860, 5412, and 6561 Å, *N*-shell transitions. Helium is normally found in EBIT as a background gas due to the inherent difficulty of pumping it out. It may enter the vacuum chamber by penetrating Be windows used to separate EBIT's high vacuum and He-filled x-ray spectrometers, or via diffusion through the transport lines that lead to the liquid He cooled superconducting Helmholtz coils used to compress the electron beam.

A spectrum of argon taken with the 300 groove/mm grating is shown in Fig. 3. The electron beam energy was 10 keV with a current of 70 mA. The spectrum is a composite from seven individual measurements each integrated for 1 min. Again several intense features are notable in the entire wavelength range, such as the lines at 4412 Å Ar XIV, 4685 Å He II, 5534 Å Ar X, 5944 Å Ar XV, and 6561 Å He II. As in the case of krypton, many of the lines in the argon spectrum are as yet unidentified. The possible identification, however, can be helped by taking systematic energy steps of the electron beam that determine the particular charge state from which each line arises. We point out that in both spectra the dominant lines belong to magnetic dipole ($M1$) transitions in highly charged ions of Ar and Kr. This makes EBIT almost an engine for the production and study of these forbidden transitions. A detailed analysis of all of this is still in progress.[9,12] For the 300 groove/mm grating, we determined a resolving power of 650 at 4600 Å.

B. VUV transitions

The quantum efficiency of the CCD detector is at a minimum in the vacuum ultraviolet wavelength range, leading one to expect to find only the stronger lines of candidate ions in this region. The Li-like resonance lines of $[1s^2 2p(^2P_{3/2}) \rightarrow 1s^2 2s(^2S_{1/2})$ and $1s^2 2p(^2P_{1/2}) \rightarrow 1s^2 2s(^2S_{1/2})]$ for C^{3+} (1548.2 and 1550.8 Å, respectively) and O^{5+} (1031.9 and 1037.6 Å, respectively) are some of the most intense and easily excited transitions in the VUV. As such they serve as a good test case for the exploration of the VUV using EBIT. Injection of CO_2 into EBIT provided both of these elements for observation using the 600 grooves/mm grating. Work is in progress to use iridium-coated gratings with 600 and 3600 grooves/mm, blazed at 900 and 600 Å, respectively, to access this region with greater efficiency and higher dispersion, and to incorporate a low-noise, fast-response detector to measure the transition rates of some of these lines. The technique of making lifetime measurements on an EBIT has been established using EBIT in the so-called magnetic trapping mode.[13] This mode occurs when the electron beam is quickly extinguished so that the highly charged ions are left to relax while still being trapped by the applied drift tube potential well and the magnetic field of the superconducting Helmholtz coil that is normally required for compression of the electron beam. Ion storage times are only on the order of a few seconds, but are clearly sufficient to measure millisecond lifetimes.

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